F_π: a *Must Do* at 12 GeV

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Hall C 12 GeV CDR Workshop
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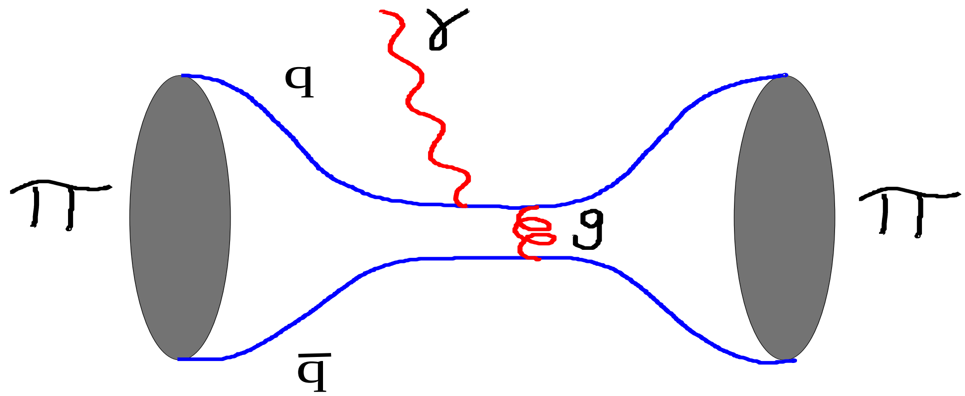
I. Introduction

II. Recent Results and Upcoming Run

III. F_π at 12 GeV

F_π in pQCD



Farrar and Jackson calculated the normalized, leading asymptotic Q^2 dependence of the pion form factor[1] as:

$$F_\pi = -2\frac{f_\pi^2}{bQ^2 lnQ^2}$$

$$Q^2 F_\pi = \frac{-2f_\pi^2}{b lnQ^2}$$

where $b = (11 - 2N_f/3)/(16\pi^2)$, and f_π is the pion decay constant from $\pi^+ \rightarrow \mu^+ + \nu$.

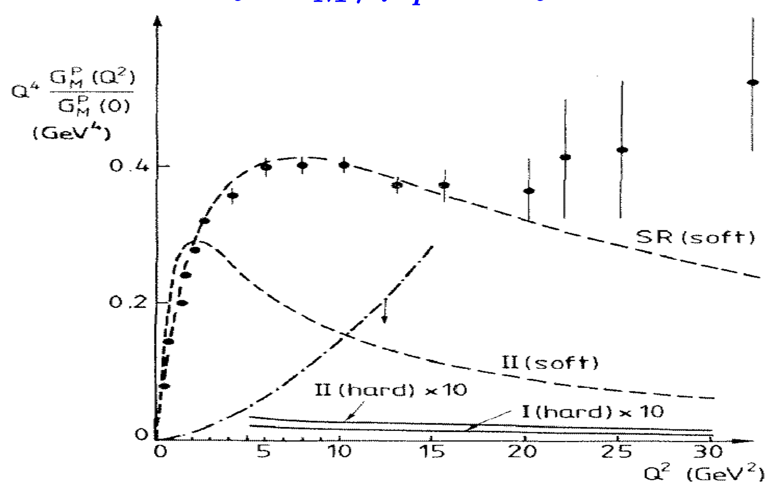
This asymptotic normalization does not exist in the case of the nucleon form factors. There is a genuine *prediction* for F_π at large Q^2.

[1] PRL **43**, 246 (1979)

The Pion as a pQCD Laboratory

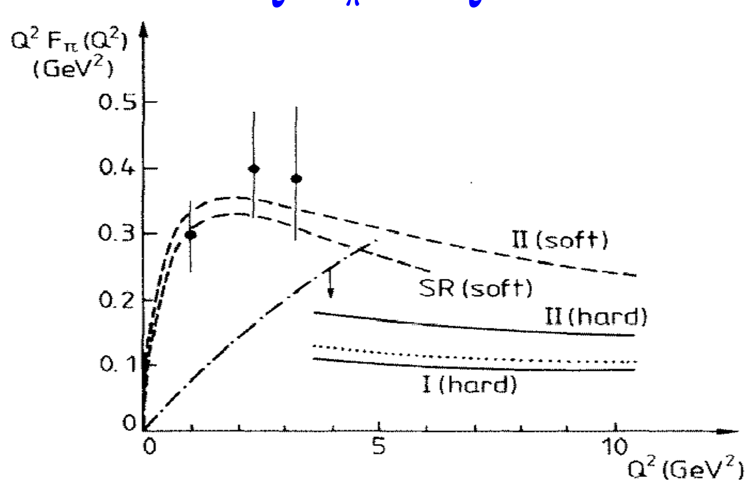
Isgur and Llewellyn-Smith[2] estimated that perturbative contribution to G_M^p (the magnetic form factor) at $Q^2 = 5$ is $\leq 1\%$

$Q^4 G_M^p/\mu_p$ vs Q^2



Meanwhile, the perturbative contribution to F_π at $Q^2 = 5$ may be $\simeq 50\%$.

$Q^2 F_\pi$ vs Q^2

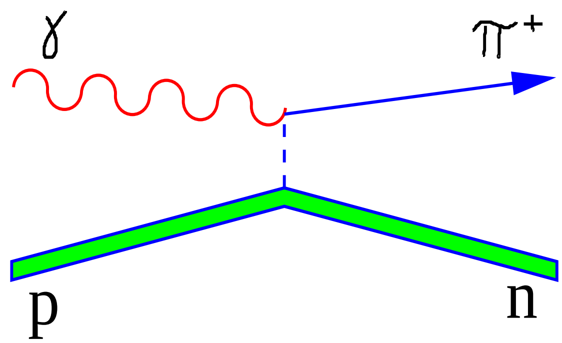


[2] PRL 52, 1080 (1984)

F_π by Pion Electroproduction

Without an e-π collider, F_π can only be determined at $Q^2 \geq 0.5$ via pion electroproduction.

The target is the virtual pion cloud of the proton:



For unpolarized $p(e, e'\pi^+)n$ scattering

$$\frac{d\sigma}{dt} = \sigma_T + \epsilon\,\sigma_L + \epsilon\cos 2\phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\,\sigma_{LT}$$

and for small -t, σ_L dominates because the interference terms vanish and due to the proximity to the pion pole:

$$\sigma_L \propto \frac{-2tQ^2}{(t-m_\pi^2)^2} \cdot g^2_{\pi NN}(t) \cdot F_\pi^2$$

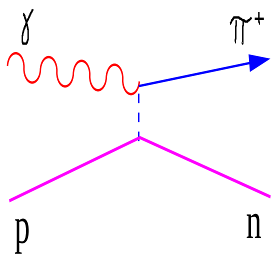
with σ_L dominating due to the proximity of the pole.

In practice one must extract F_π from a model which is gauge invariant, valid at large W to avoid the resonance region, and which accounts for rescattering. (More on this later.)

Mandelstam t and t_{min}

In terms of experimentally accessible 4-vectors:

$$t \equiv (\gamma_v - \pi)^2 = -Q^2 + m_\pi^2 - 2\nu E_\pi + 2\nu p_\pi cos\theta_{q\pi}$$

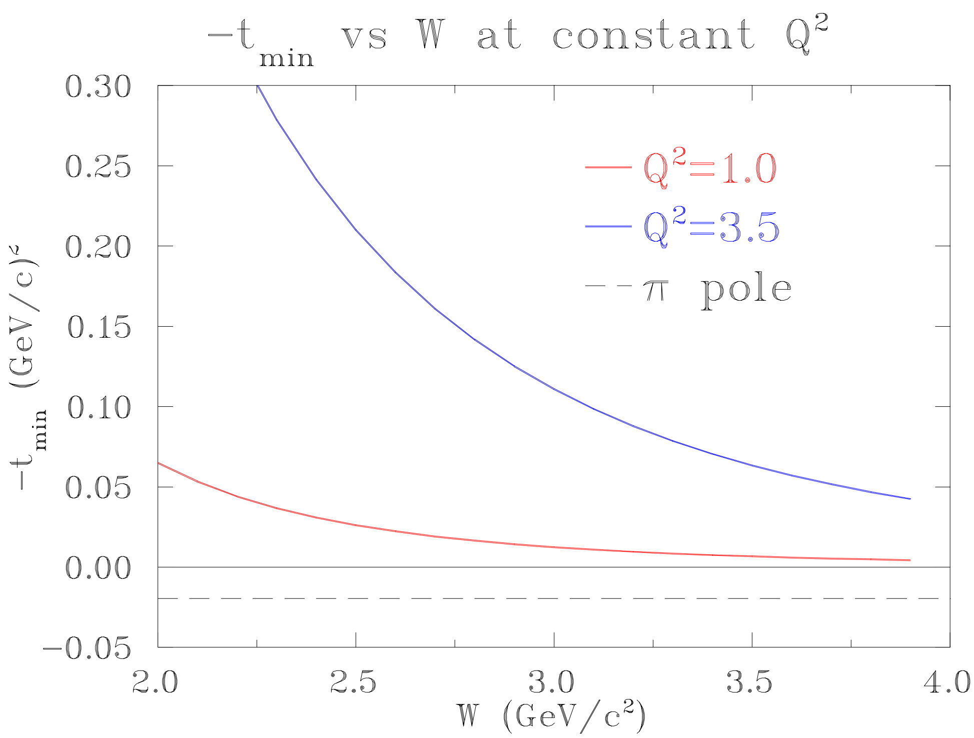


For more insight, in the non-relativistic limit the momentum transfer is:

$$t \equiv (p - n)^2 \simeq -P_n^2$$

Thus $-t$ is simply the squared nucleon recoil momentum.

For fixed Q^2, one can approach the pole most closely by letting $\theta_{q\pi} = 0$ and making the energy transfer large:



F_π Technical Issues

• Small π spectrometer angles

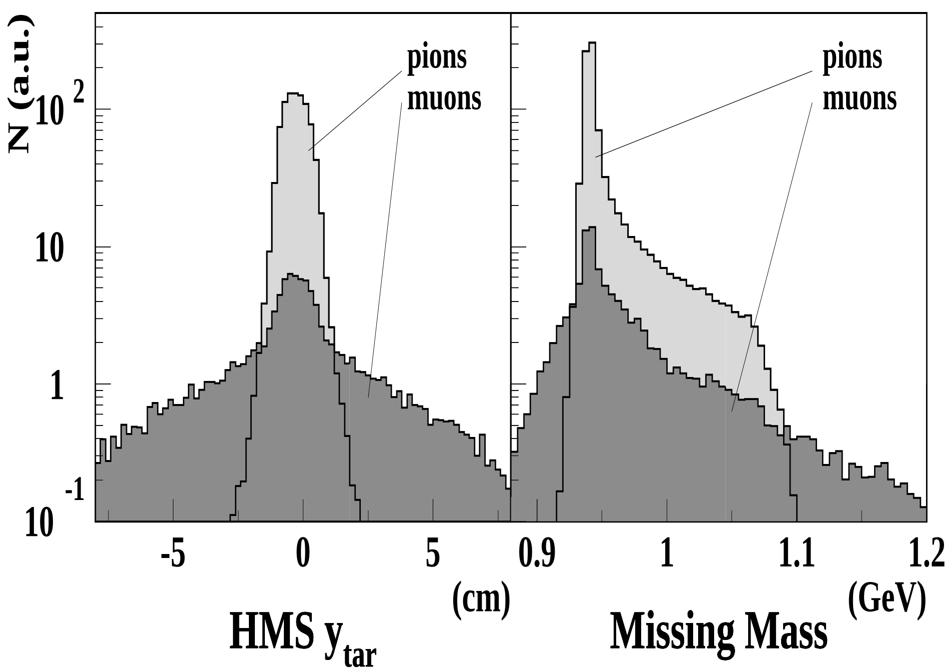
Moved HMS quad string backward
Refit the HMS optics

• L-T separation:

2 beam energies per Q^2 (scheduling issue)
good systematics control over a wide range of scattered electron $\vec{p}$
careful calibration using $p(e, e'p)$ to determine offsets

• Contamination by unflagged μ's from π decay (5%)

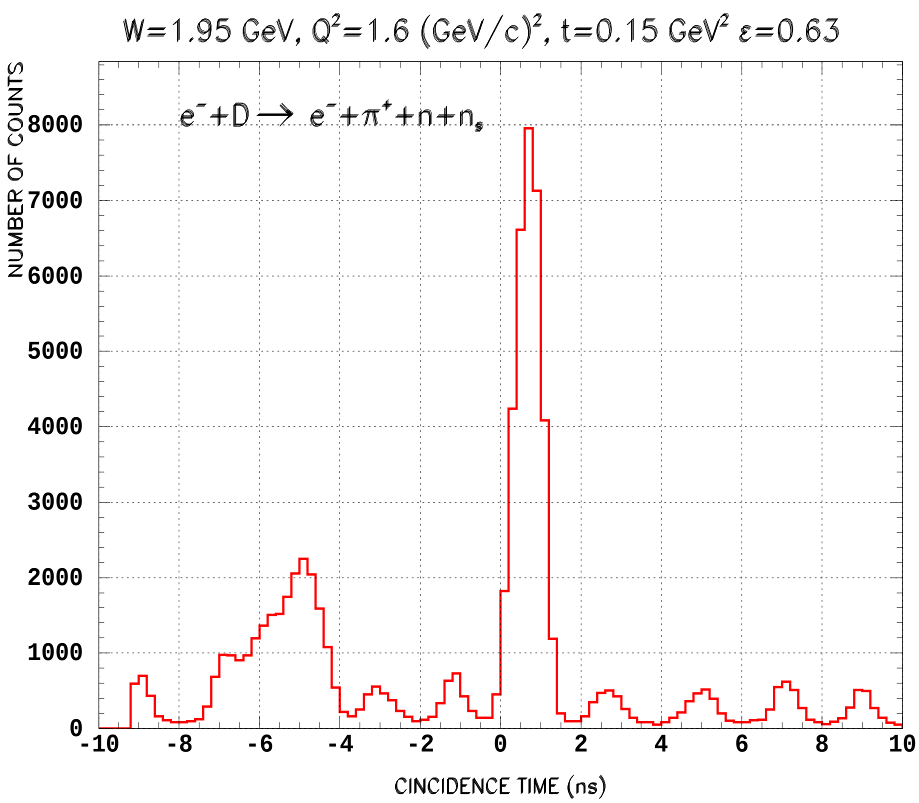
Monte Carlo takes this into account.



Removing Accidental Coincidences: A Cut on Coincidence Time

A beam burst hits the target every 2 nsec. In accidental coincidences, the electron and pion originated from reactions in *different* beam bursts.

Shown are well-separated peaks for real $e \cdot \pi^+$ and $e \cdot p$ coincidences. For momenta below 6 GeV/c, this cut helps get rid of unwanted protons.



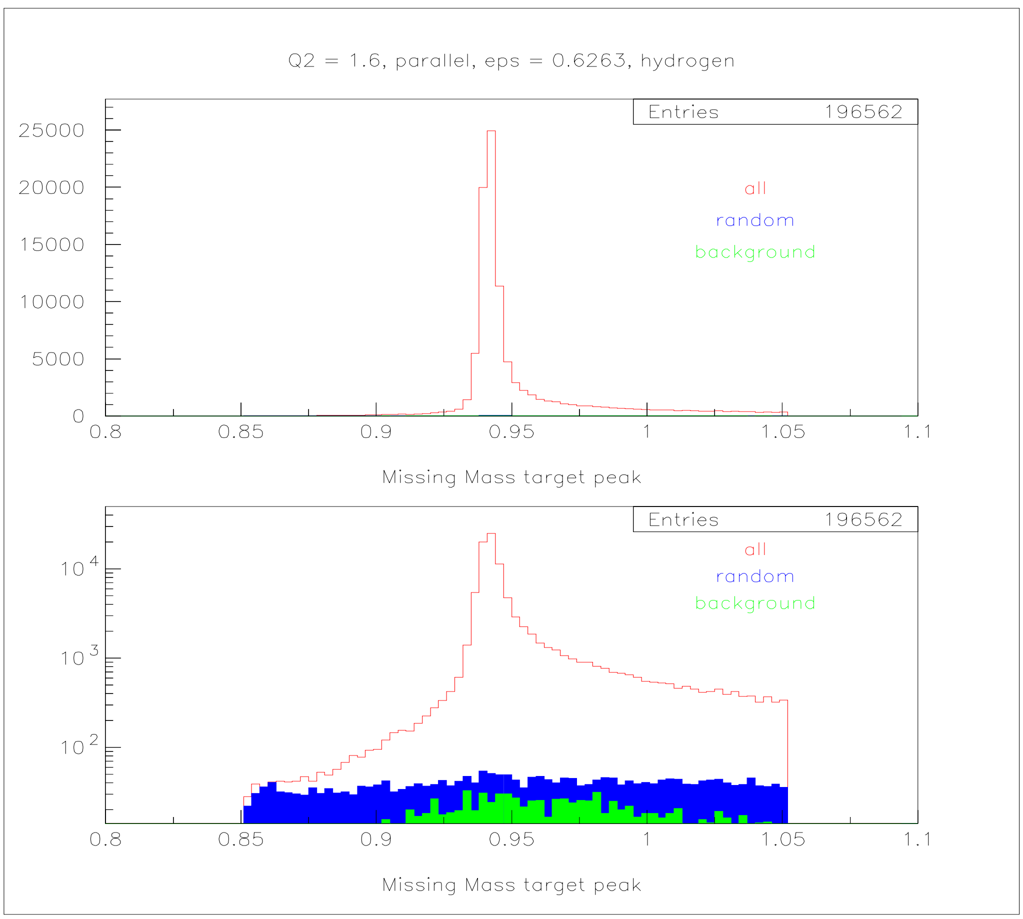
Only events in the real $e \cdot \pi^+$ peak are accepted. A few underlying random coincidences must be subtracted.

Reconstructed Missing Mass: a Cut to Ensure Exclusivity

For the reaction e + p $\longrightarrow$ e' + π^+ + X,

$$MM_X = \sqrt{(e + p - e' - \pi^+)^2}$$

On linear and log scales, respectively, one finds

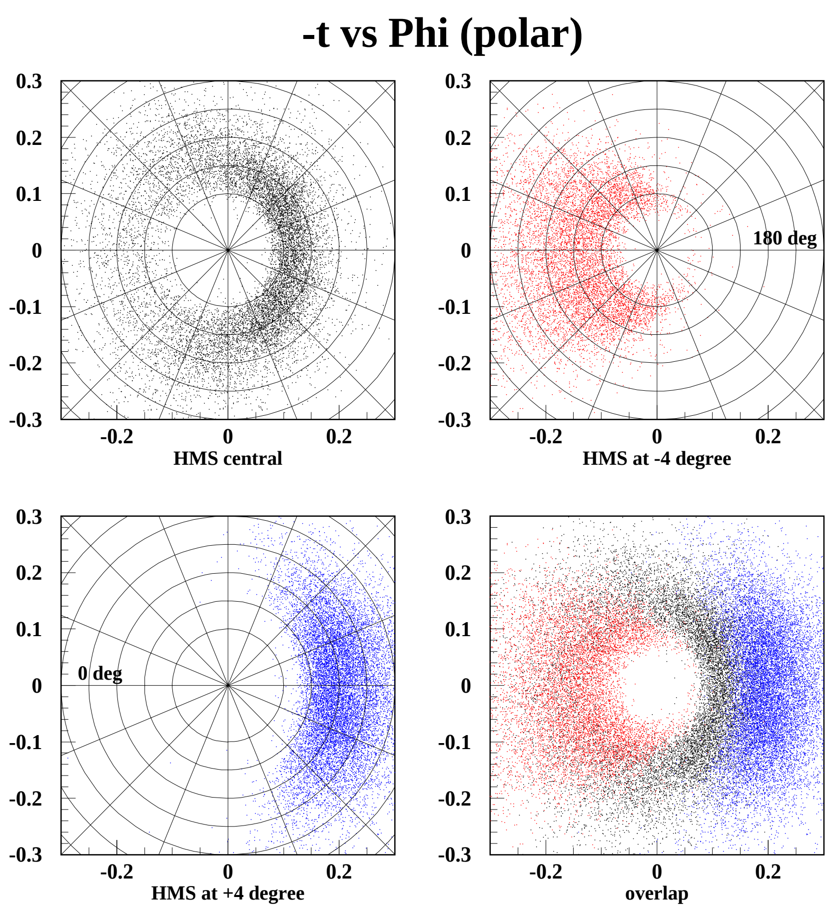


A cut which constrains $MM_X \simeq M_{neutron}$ removes backgrounds with higher inelasticity and suppresses random coincidences.

Extracting Response Functions from Cross Sections

$$\frac{d\sigma}{dt} = \sigma_T + \epsilon\,\sigma_L + \epsilon\cos 2\phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\,\sigma_{LT}$$

Adequate coverage in $\phi_{q\pi}$ for each $-t$ bin is needed to separate the response functions. The pion spectrometer was scanned about $\vec{q}$.



A fit then determines $\sigma_T + \epsilon\,\sigma_L$, σ_{TT}, and σ_{LT}.

Reaction Mechanism Test: π^-/π^+ Ratios

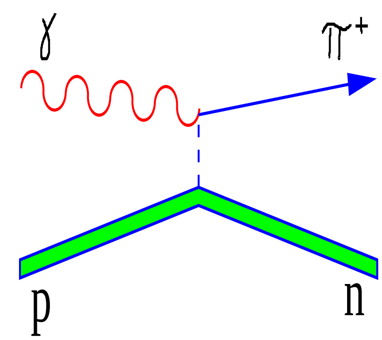
Using a Deuterium target, one can measure the ratio

$$R_L \equiv \frac{\sigma_L(\gamma + n \to \pi^- + p)}{\sigma_L(\gamma + p \to \pi^+ + n)}$$

Pion Exchange

The coupling of γ_v to $\pi^\pm$ is the same magnitude. Assuming dominance of this amplitude

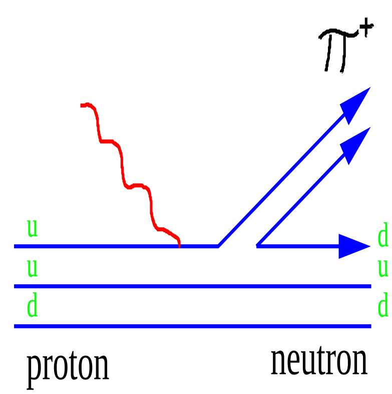
$$R_L \simeq \frac{Q^2_{\pi^-}}{Q^2_{\pi^+}} = 1$$



Quark Knockout

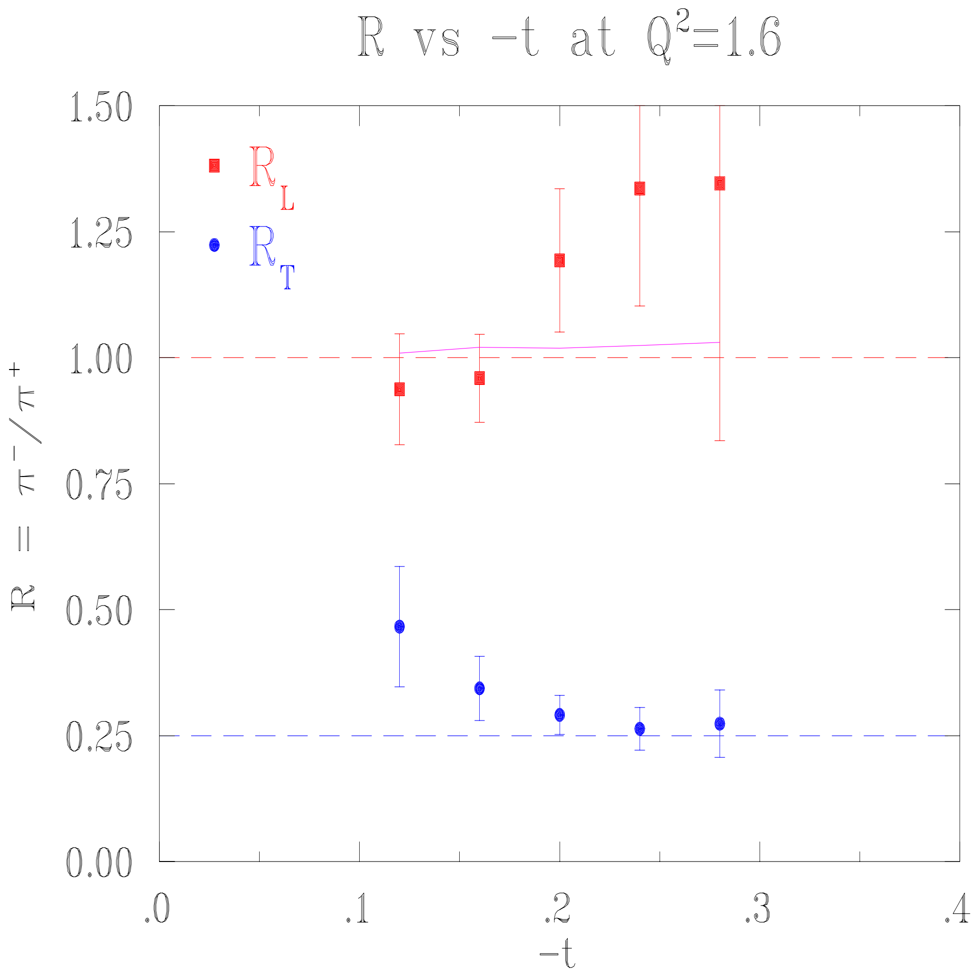
In this potential background scenario[8], forward π^- are the result of Q=-1/3 down quarks being knocked out of the neutron, and forward π^+ are the result of Q=+2/3 up quarks ejected from the proton. Assuming dominance,

$$R \simeq \frac{2Q_d^2}{2Q_u^2} = \frac{(-1/3)^2}{(+2/3)^2} = 1/4$$



[8] Carlson and Milana, PRL **65** 1717 (1990)

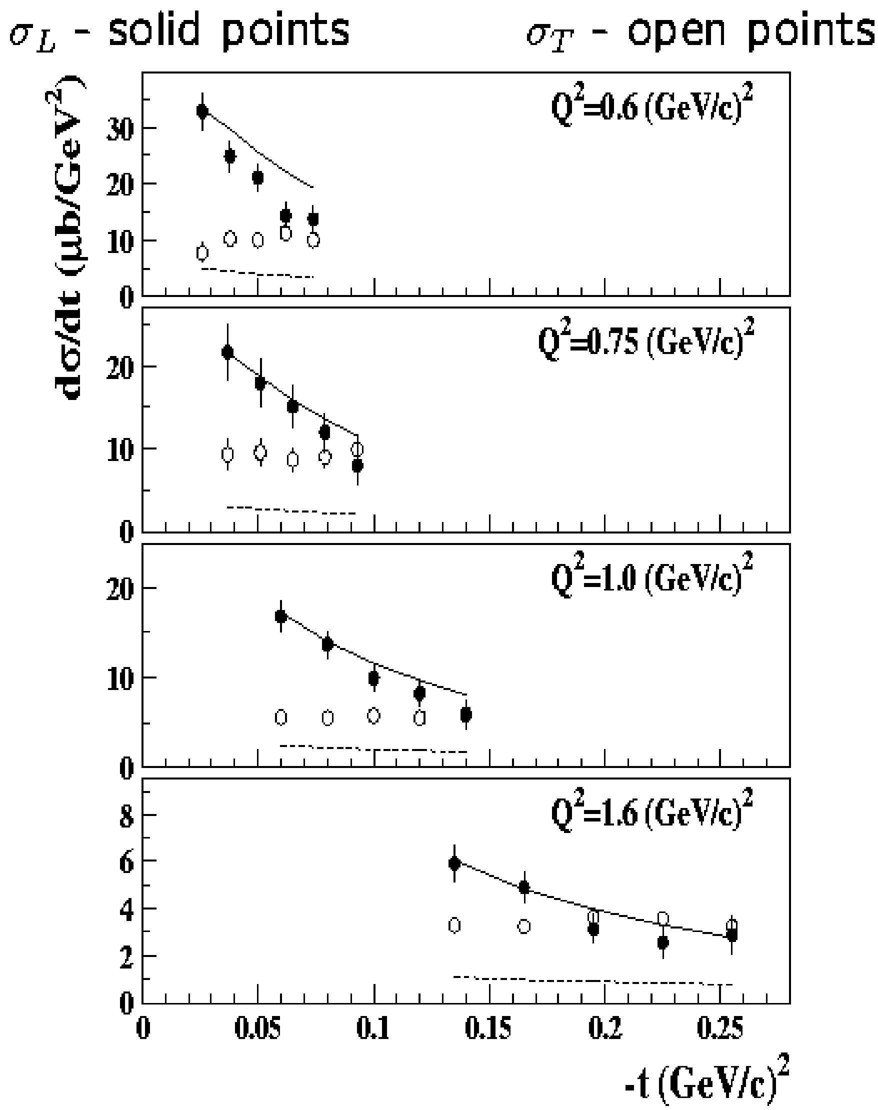
JLab First *Separated* π^-/π^+ Ratios: Test of the Reaction Mechanism



The longitudinal ratio is $\simeq 1$ at low $-t$. This, and the strong $-t$ dependence in σ_L, are consistent with pion pole dominance.

Good news for F_π!

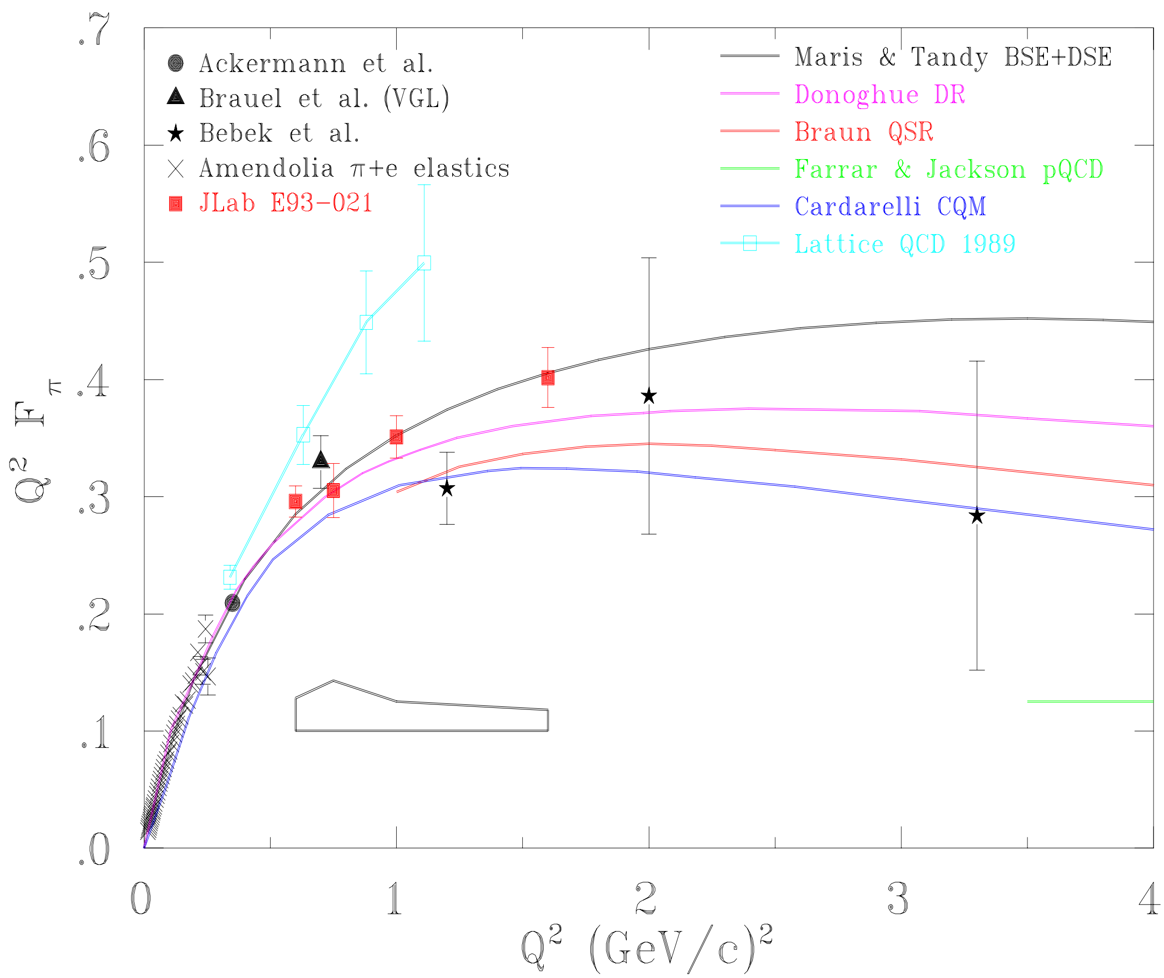
JLab Separated Cross Sections vs VGL Regge



Longitudinal -

- F_π is chosen so the VGL curve passes through the data at t_{min}.
- At most Q^2, the data are slightly steeper than the calculation.
- Our errors on F_π take into account this difference in slope, which was treated as due to a destructively interfering background.

Present World Data for F_π

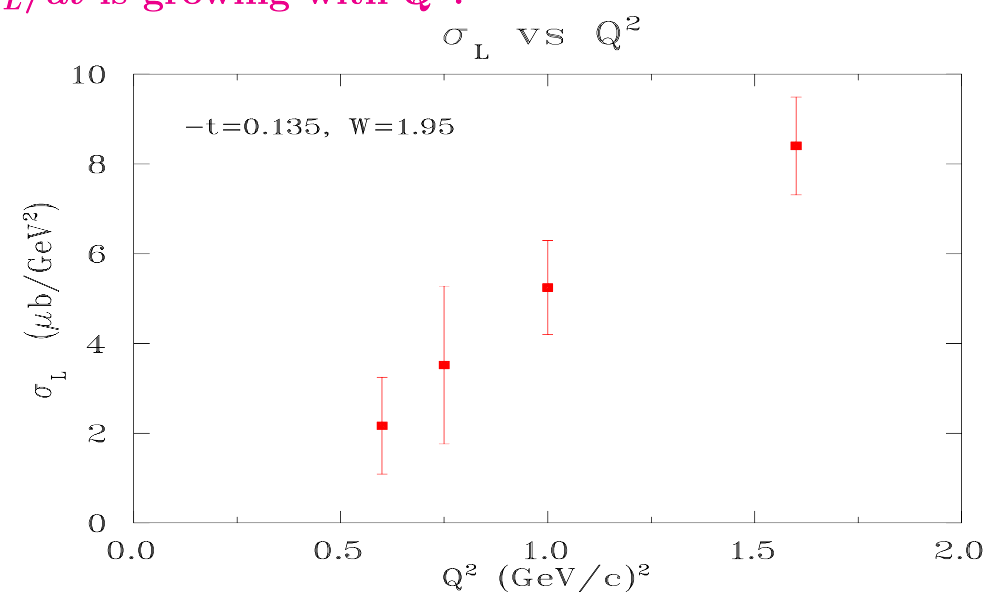


- Our higher Q^2 data[13] are larger than the trend of the older data.
- Low Q^2 lattice calculations need to be revisited.
- F_π is quite hard. The Maris and Tandy curve (which fits very well) is nearly indistinguishable from a monopole form factor which describes the pion radius.
- Many models fitted to the old data are systematically low. Serious models of F_π should have their free parameter(s) fitted to data in a different sector, and then used to *predict* F_π.

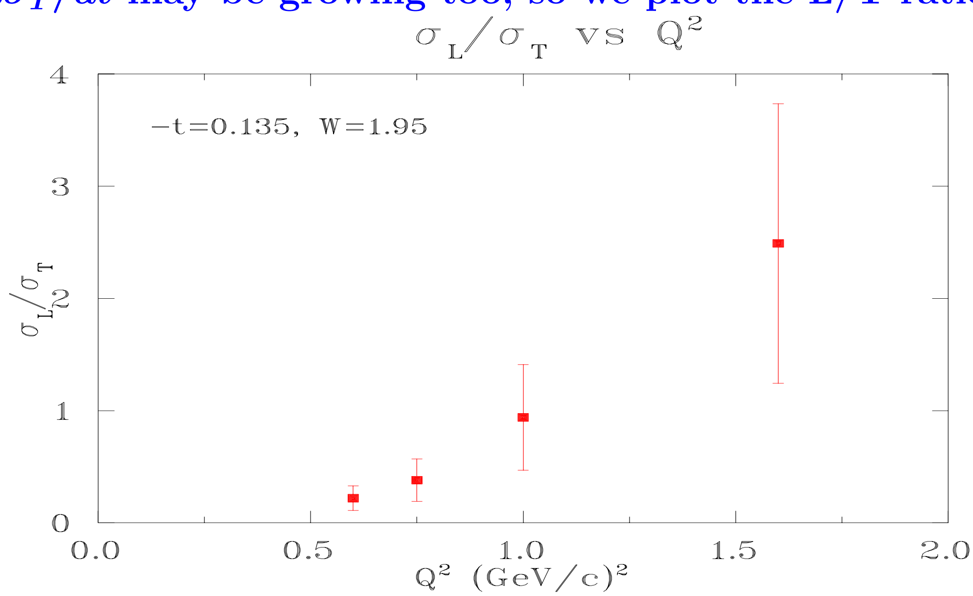
[13] J. Volmer et al, PRL 86, 1713 (2001)

Q^2 Dependence of σ_L and σ_T

Taking care to interpolate our data to a fixed $-t$ and W, we find that $d\sigma_L/dt$ is growing with Q^2:



But $d\sigma_T/dt$ may be growing too, so we plot the L/T ratio:



and find σ_L/σ_T is growing even FASTER.

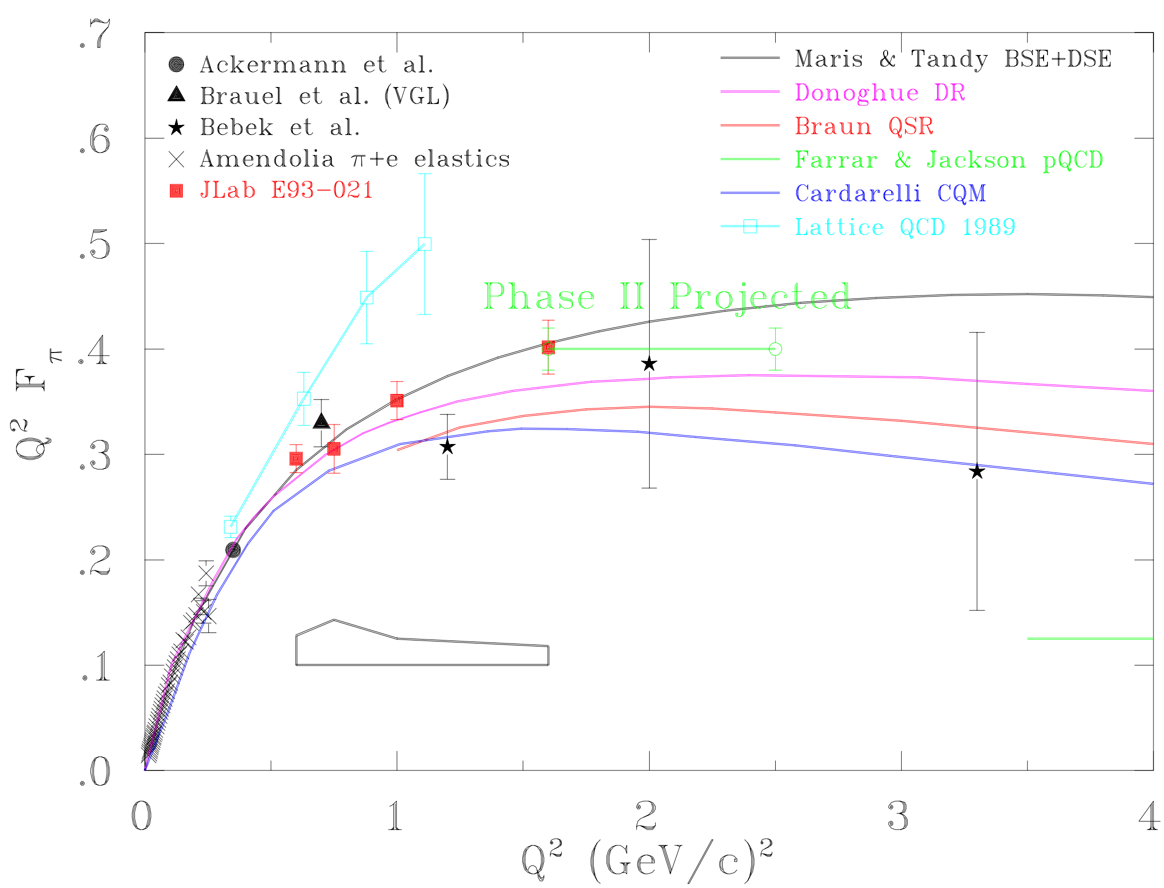
L-T separations can be expected to become *easier*!

What Else With 6 GeV Beam?

Phase II in 2003

Our Phase I measurement was limited by 4 GeV beam. Our next measurements will be limited by spectrometer angle and momentum ranges. Our goals will be:

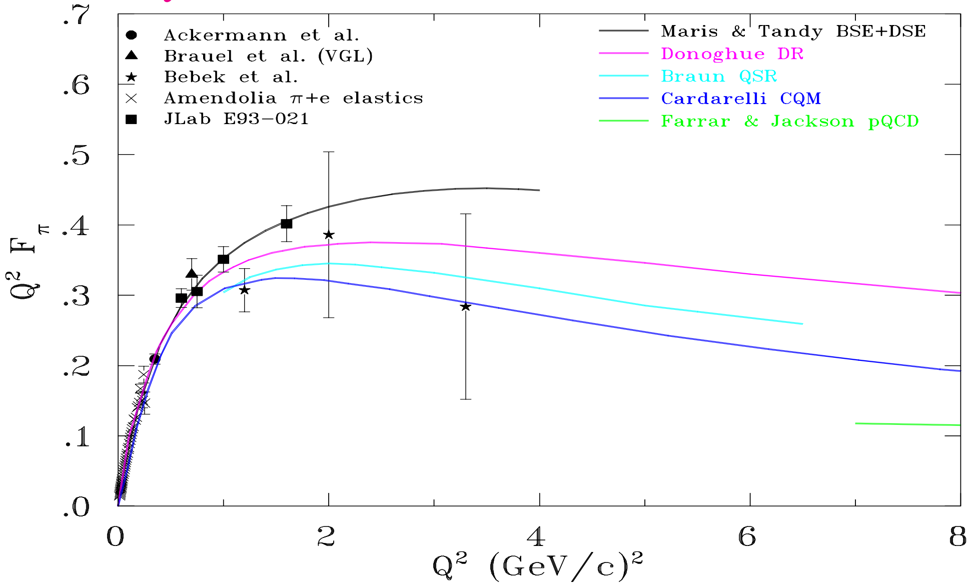
- Increase our maximum Q^2 for F_π from 1.6 to 2.5
- Repeat Q^2=1.6 at higher W to study data vs Regge systematics.



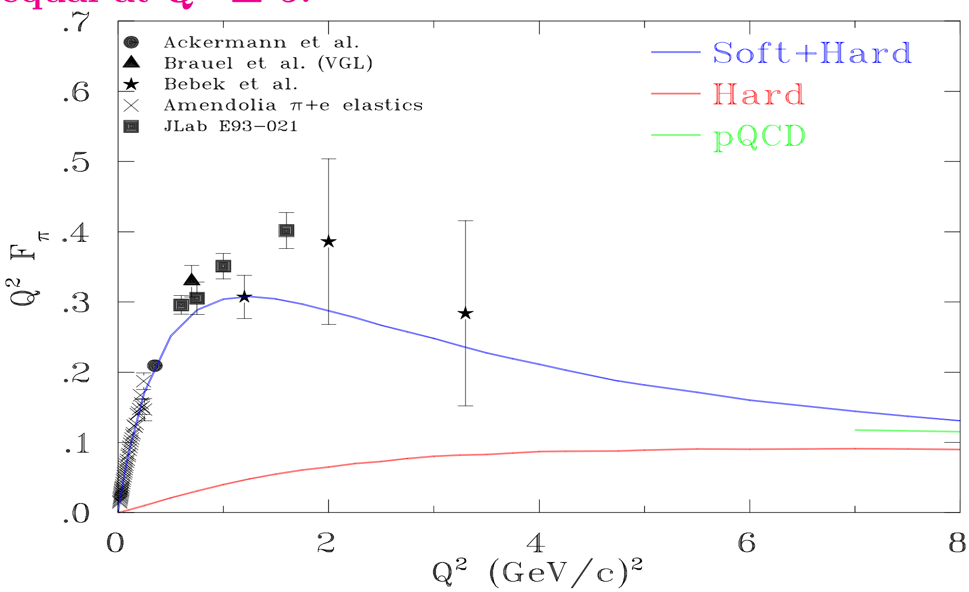
This will complete the HMS-SOS 6 GeV F_π program.

F_π at Intermediate Q^2: Theoretical Calculations

A small selection of available models shows significant differences at intermediate Q^2:



Kisslinger and Wang[14] found the soft and hard contributions to be roughly equal at $Q^2 \simeq 5$.

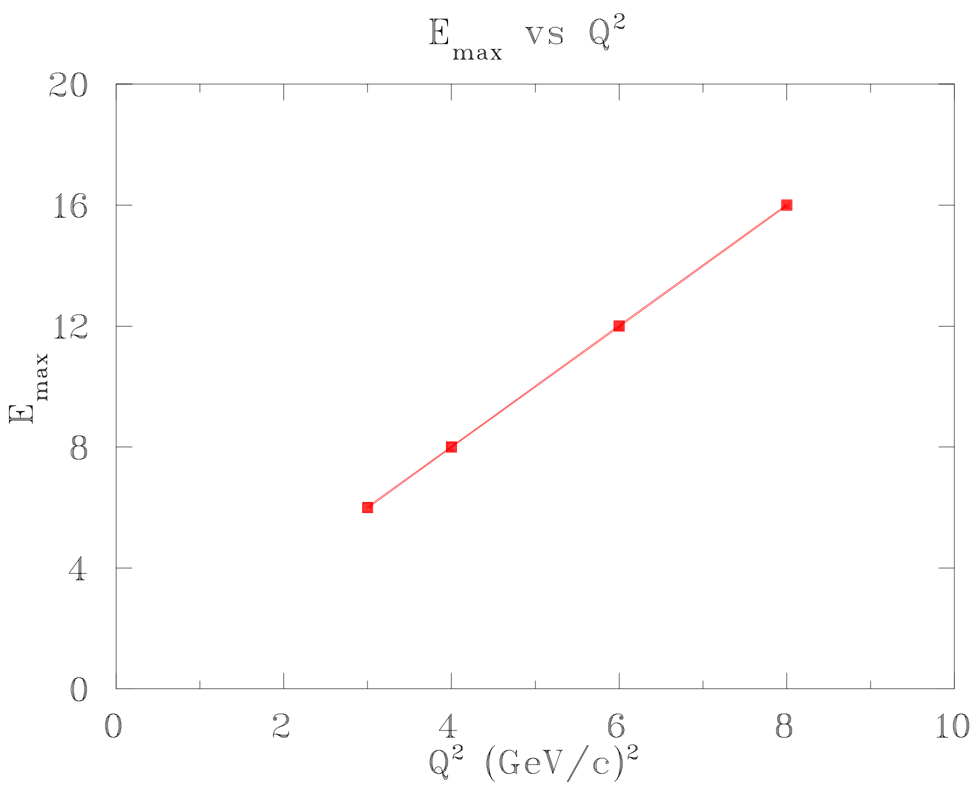


[14] NP B399 (1993) 63

Beam Energy Needed for Higher Q^2

Assumptions:

- $-t_{min} \leq 0.20$ (ie, $\leq 10m_\pi^2$)
- $\Delta\epsilon \geq 0.25$
- HMS-SHMS



12 GeV beam is needed for $Q^2 = 6$.

16 GeV beam is needed for $Q^2 = 8$.

F_π at higher Q^2 requires a high beam energy!

Kinematics of L-T Separations at Higher Q^2

$$\boxed{p(e, e'\pi^+)n}$$

Q^2 = 5. W = 3.25 t_{min} = -0.15

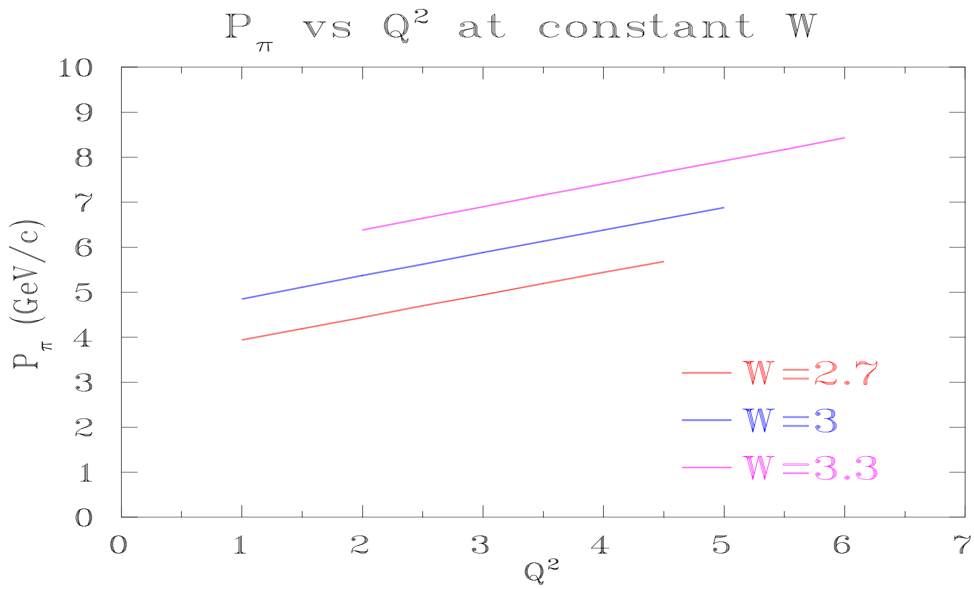
$P_\pi = 7.74\ GeV/c$

E_{beam} (GeV)	E' (GeV)	$\theta_{e'}$ (deg)	θ_π (deg)	ϵ
9.1	1.27	38.3	5.5	0.24
10.0	2.17	27.7	7.1	0.39
10.9	3.07	22.2	8.2	0.49
				$\Delta\epsilon = 0.25$
11.1	3.27	21.3	8.4	0.51
11.5	3.67	19.8	8.8	0.55
11.9	4.07	18.4	9.1	0.59
				$\Delta\epsilon = 0.35$

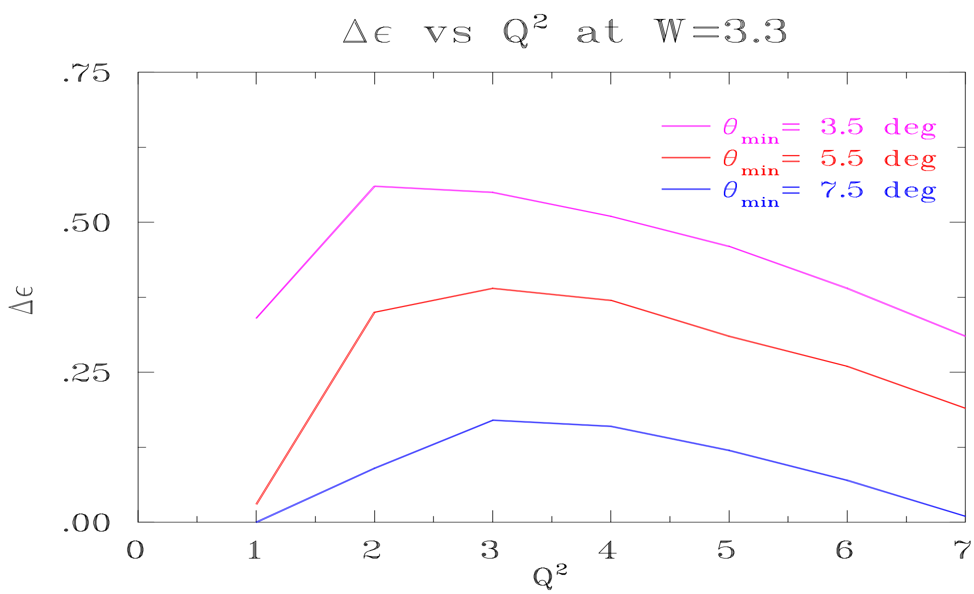
- 10.9 GeV beam is good. 11.9 GeV beam is better.
- No stringent demands on the electron arm.
- Pion momenta are quite large.
- Pion angles are quite small.

Kinematics of L-T Separations at Higher Q^2

A maximum central momentum of about 9 GeV/c is needed.



A minimum central scattering angle of about 5.5° is needed.

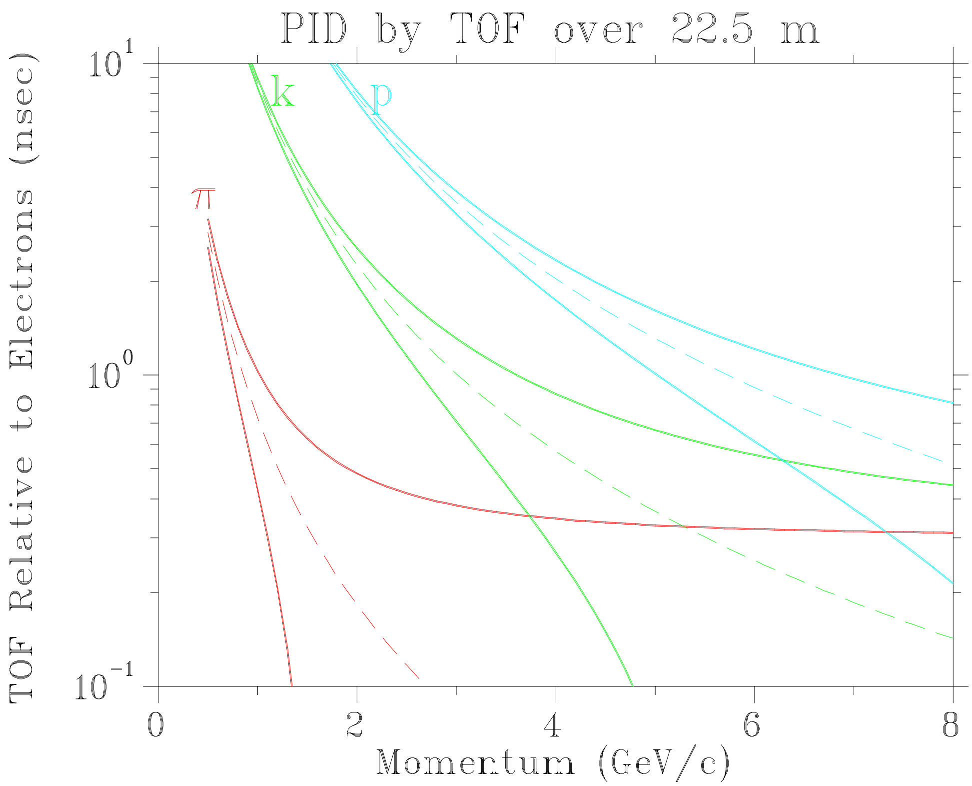


To measure F_π at large Q^2, a new high momentum, small angle spectrometer must be built.

Particle Identification at 12 GeV

Presently at JLab, many experiments still discriminate hadrons by Time of Flight. Much of this capability will be lost at 12 GeV.

Assuming a conservative 200 ps time resolution (rms) and the criterion that separation should be at least 3σ:



- **$\pi - k$ discrimination is lost around 3.8 GeV/c**
- **$\pi - p$ discrimination is lost around 7.3 GeV/c**

Threshold Cerekov detectors will be much more important at 12 GeV.

Basic parameters of the SHMS

Parameters which proposal writers care about:

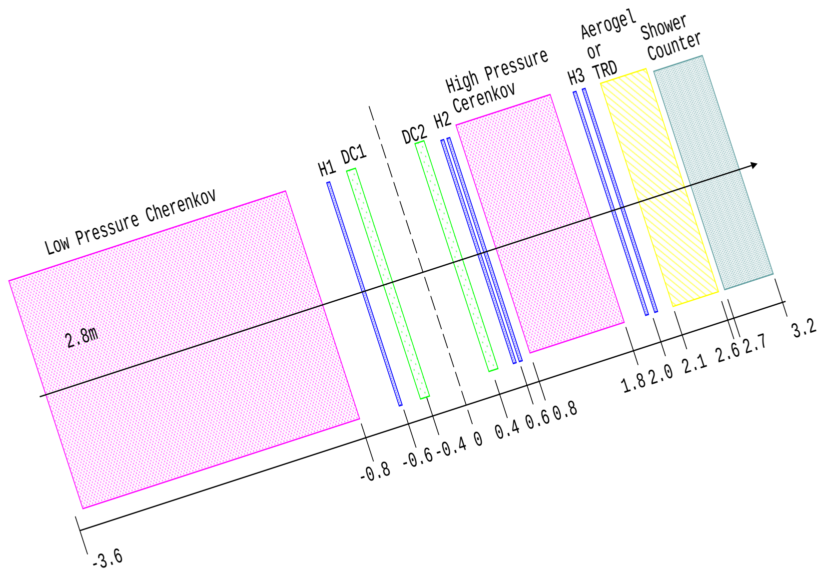
Max. Central Momentum	11 GeV/c
Min. scattering angle	5.5°
Momentum acceptance	20%
Momentum resolution	.15%-.2%
xptar,yptar resolution	1-2 mrad, 1-2 mrad
Ytar resolution	.2-.6 cm
Vertical acceptance	±42 mrad
Horizontal acceptance	±14 mrad
Solid angle	2 msr
Opening angle with HMS	16°

Parameters which only an optician could love:

Configuration	QQ(DQ)
Bend Angle	18.4°
Focusing mode	Double
Max. rigidity	400 kG-m
Dispersion	1.764 cm/%
D/M	1.20 cm/%
Mx	1.47
My	1.02
Focal plane angle	4.88°
Focal plane dimension	40 cm (X) x 20 cm (Y)
Optical length	18.5 m

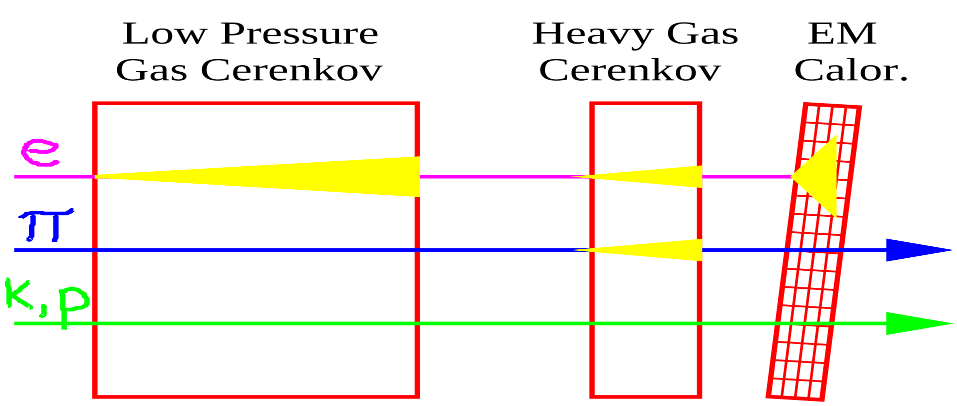
SHMS Detectors

The SHMS detectors will be broadly similar to the present HMS detectors, with several critical modifications for PID at large momenta:



• *e − hadron* discrimination will require a longer, lower pressure gas Cerenkov.

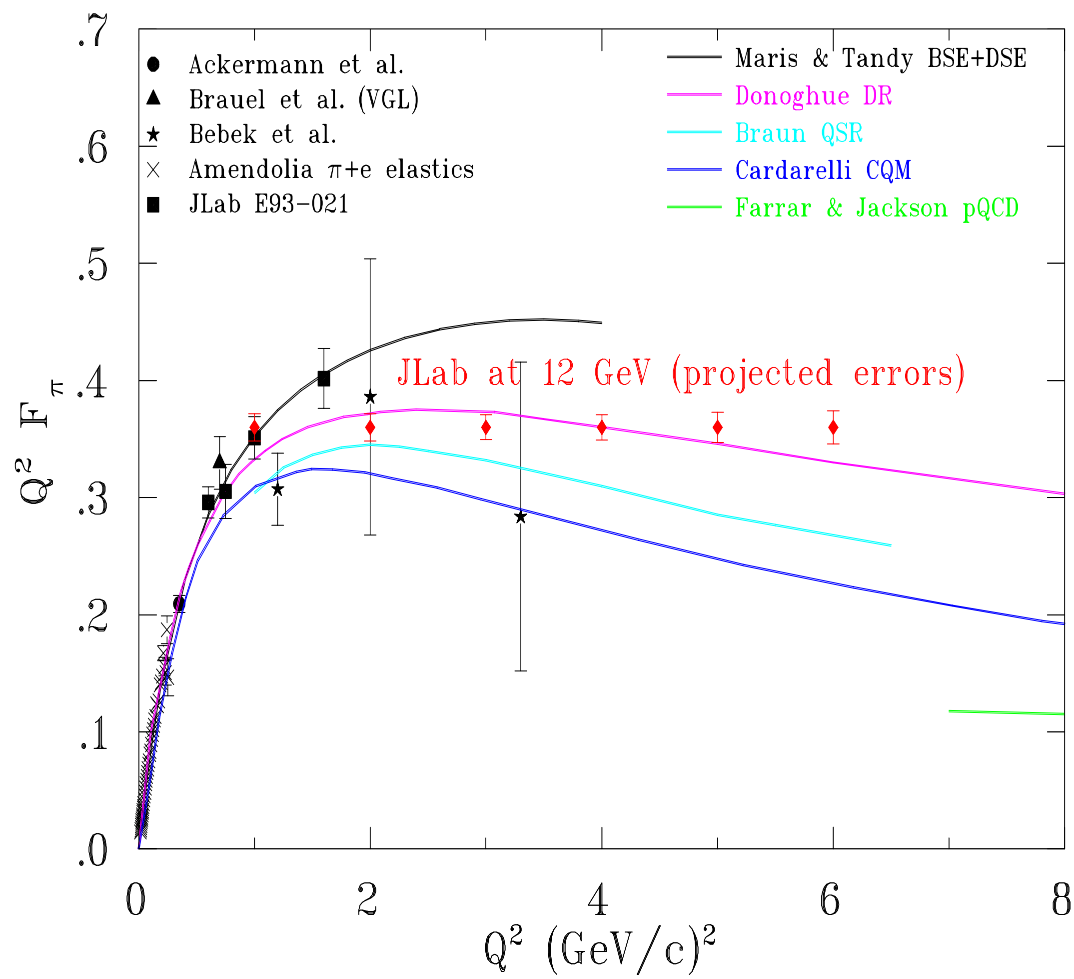
• *π − k* discrimination will require a heavy gas Cerenkov.



Projected Errors for F_π at 12 GeV

Running Conditions

- HMS-SHMS
- 100 days
- 4cm LH_2 target
- 50 μA



F_π at 12 GeV Summary

- **F_π was determined for Q^2 = .6 - 1.6:**

  Very soft models for F_π are ruled out.

  Q^2F_π is not yet asymptotic.

- **Outlook for higher Q^2 remains good:**

  Longitudinal π^-/π^+ ratio suggests dominance of pion exchange,

  L/T ratio is increasing with Q^2.

- **A new measurement is planned for 2003:**

  to reach Q^2= 2.5,

  to study data vs Regge slope discrepancies.

- **A new spectrometer is needed for light meson electroproduction studies at 12 GeV:**

  Central momenta to at least 9 GeV/c,

  Central angles as low as 5.5°,

  Clean pion identification for P_π = 4-9 GeV/c.

  The proposed SHMS suits our needs!

F_π as measured by SHMS-HMS at 12 GeV is the only way to observe the transition between the confinement and perturbative regimes in an exclusive reaction.